REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
07-03-2008	Final Report	16-Jun-2003 - 30-Sep-2006

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Final Report for Strategic Applications of Ultra-cold Atoms	DAAD19-03-1-0106
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 611103
6. AUTHORS Prentiss, Vuletic, Kasevich, Ketterle, Meystre	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES	8. PERFORMING ORGANIZATION REPORT NUMBER
Stanford University Office of Sponsored Research Board of Trustees of the Leland Stanford Junior University Stanford, CA 94305 -	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	ARO
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) 45592-PH-MUR.1

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

This consortium established a focused collaborative program to advance matter wave sensors. We combined atom interferometry with atom lasers and atom waveguides with the prospect of improving the sensitivity of such sensors by orders of magnitude as compared with existing state-of-the-art sensors. We identified, explored and exploited fundamental scientific possibilities surrounding the production, manipulation and detection of ultra-cold atoms for a variety of sensing applications. Such sensors include gravimeters, gravity gradiometers, gyroscopes, magnetometers and frequency standards and have applications in science and technology and within the DoD. Sensitive and accurate inertial force sensors can be used in

15. SUBJECT TERMS

atom optics, atom interferometry, Bose-Einstein Condensation

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Mark Kasevich
UU	U	U	SAR		19b. TELEPHONE NUMBER 650-723-4356

Report Title

Final Report for Strategic Applications of Ultra-cold Atoms

ABSTRACT

This consortium established a focused collaborative program to advance matter wave sensors. We combined atom interferometry with atom lasers and atom waveguides with the prospect of improving the sensitivity of such sensors by orders of magnitude as compared with existing state-of-the-art sensors. We identified, explored and exploited fundamental scientific possibilities surrounding the production, manipulation and detection of ultra-cold atoms for a variety of sensing applications. Such sensors include gravimeters, gravity gradiometers, gyroscopes, magnetometers and frequency standards and have applications in science and technology and within the DoD. Sensitive and accurate inertial force sensors can be used in covert/passive navigation, precision guidance, underground structure detection, gravitational mapping, etc. They are non-emanating and capable of operating in a jammed-GPS environment.

We sought to build awareness of DoD needs critical to national defense at the graduate training level, and to establish a dialogue between DoD and industrial researchers/managers and PhD trainees.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

W. Zhang, H. Pu, C. P. Search, P. Meystre, and E. M. Wright, "Two-fermion bound state in a Bose-Einstein condensate", Phys. Rev. A (Rapid Communications) 67, 021601(R) (2003).

W. Zhang, C. P. Search, H. Pu, P. Meystre, and E. M. Wright, “Feshbach resonance-induced atomic filamentation and quantum pair correlation in atom laser beam propagation,” Phys. Rev. Lett. 90, 140401 (2003)..

C. P. Search and P. Meystre, “Noise limits on matter-wave interferometry using degenerate quantum gases,” Phys. Rev. A (Rapid Communications) 67, 061601(R) (2003).

H. Pu, L. O. Baksmaty, W. Zhang, N. P. Bigelow, and P. Meystre, “Effective mass analysis of Bose-Einstein condensates in optical lattices — Stabilization and levitation,” Phys. Rev. A 67, 043605 (2003).

H. Christ, C. P. Search, and P. Meystre, “Dynamics of Fermionic Four-Wave Mixing,” Phys. Rev. A 67, 063611 (2003).

T. Miyakawa, H. Christ, C. P. Search, and P. Meystre, "Four-wave mixing in degenerate Fermi gases: Beyond the undepleted pump approximation," Phys. Rev. A 67, 063603 (2003).

Weiping Zhang, Ewan M. Wright, Han Pu, and Pierre Meystre, "A fundamental limit for integrated atom optics with Bose-Einstein condensates," Phys. Rev. A 68, 023605 (2003).

Chris P. Search and P. Meystre, “Phase conjugation of a quantum-degenerate atomic Fermi beam,” Phys. Rev. Lett. 91, 100401 (2003).

Han Pu, Weiping Zhang, and Pierre Meystre, “Wave mixing of optical pulses and Bose-Einstein condensates,” Phys. Rev. Lett. 91, 150407 (2003).

Chris P. Search, Weiping Zhang, and P. Meystre, “A molecular micromaser,” Phys. Rev. Lett 91, 190401 (2003).

B. P. Anderson, K. Dholakia, and E. M. Wright, “Atomic-phase interference devices based on ring-shaped Bose-Einstein condensates: Two ring case,” Phys. Rev. A 67, 033601 (2003).

C. P. Search, W. Zhang, and P. Meystre, “Inhibiting three-body recombination in atomic Bose-Einstein condensates,” Phys. Rev. Lett. 92, 140401 (2004).

C. P. Search, T. Miyakawa, and P. Meystre, “A lattice array of molecular micromasers,” Optics Express 12, 30 (2004).

C. P. Search and P. Meystre, “Molecular matter-wave amplifier,” Phys. Rev. Lett. 93, 140405 (2004).

T. Miyakawa, C. P. Search, and P. Meystre, “Phase coherence in a driven double-well system,” Phys. Rev. A 70, 053622 (2004).

M. Jääskeläinen, W. Zhang, and P. Meystre, “Limits to phase resolution in matter-wave interferometry,” Phys. Rev. A 70, 063612 (2004).

D. Meiser, C. P. Search, and P. Meystre, "Diffraction of ultra-cold fermions by a quantized light fields: Standing versus traveling waves," Phys. Rev. A 71, 013404 (2005).

P. Meystre, “Nonlinear matter-wave optics of bosons and fermions,” J. Phys. B 38, S617 (2005).

P. Meystre, “From micromasers to atom optics and back,” Laser Physics 15, 99 (2005).

C. P. Search and P. Meystre, “Nonlinear and quantum optics of atomic and molecular fields,” Progress in Optics Vol. 47, p. 139-214, Edited by E. Wolf, Elsevier, Amsterdam (2005).

T. Miyakawa and P. Meystre, “Boson-fermion coherence in a spherically symmetric harmonic trap,’’ Phys. Rev. A 71, 033624 (2005).

D. Meiser and P. Meystre, “Number statistics of molecules formed by ultracold atoms,” Phys. Rev. Lett. 94, 093001 (2005).

M. Jääskeläinen and P. Meystre, “Transient dynamics of Bose-Einstein condensates in double-well potentials,” Phys. Rev. A 71, 043603

(2005).

H. Uys, T. Miyakawa, D. Meiser and P. Meystre, “Passage time statistics in the formation of ultracold dimers from fermionic atoms,” Phys. Rev. A 72, 053616 (2005).

D. Meiser, P. Meystre, and C. P. Search, "Molecule formation as a diagnostic tool for second-order correlations of ultracold gases," Phys. Rev. A 71, 033621 (2005).

O. Dutta, M. Jääskeläinen, and P. Meystre, “A polarizing beam splitter for dipolar molecules,” Phys. Rev. A (Rapid Communications) 71, 051601(R) (2005).

D. Meiser and P. Meystre, “Reconstruction of the phase of matter-wave fields using a momentum resolved cross-correlation technique,” Phys. Rev. A 72, 023605 (2005).

K. Xu, Y. Liu, J.R. Abo-Shaeer, T. Mukaiyama, J.K. Chin, D.E. Miller, W. Ketterle, K.M. Jones, and E. Tiesinga:
Sodium Bose-Einstein Condensates in an Optical Lattice.
Phys. Rev. A 72, 043604 (2005).

Y. Shin, G.-B. Jo, M. Saba, T.A. Pasquini, W. Ketterle, and D.E. Pritchard:
Optical Weak Link between Two Spatially Separate Bose-Einstein Condensates.
Phys. Rev. Lett. 95, 170402 (2005).

Y. Shin, C. Sanner, G.-B. Jo, T. A. Pasquini, M. Saba, W. Ketterle, D. E. Pritchard, M. Vengalattore, and M. Prentiss:
Interference of Bose-Einstein condensates split with an atom chip.
Phys. Rev. A 72, 021604(R) (2005).

G.K. Campbell, A.E. Leanhardt, J. Mun, M. Boyd, E.W. Streed, W. Ketterle, and D.E. Pritchard:
Photon Recoil Momentum in Dispersive Media.
Phys. Rev. Lett. 94, 170403 (2005).

D.E. Miller, J.R. Anglin, J.R. Abo-Shaeer, K. Xu, J.K. Chin, and W. Ketterle:
High-Contrast Interference in a Thermal Cloud of Atoms.
Phys Rev. A 71, 043615 (2005).

M. Saba, T.A. Pasquini, C. Sanner, Y. Shin, W. Ketterle, and D.E. Pritchard:
Continuous measurement of the relative phase of two Bose-Einstein condensates using light scattering.
Science 307, 1945-1948 (2005)

J.R. Abo-Shaeer, D.E. Miller, J.K. Chin, K. Xu, T. Mukaiyama, and W. Ketterle:
Coherent Molecular Optics using Sodium Dimers.
Phys. Rev. Lett. 94, 040405 (2005).

Y. Shin, M. Saba, M. Vengalattore, T. A. Pasquini, C. Sanner, A. E. Leanhardt, M. Prentiss, D. E. Pritchard, and W. Ketterle:
Dynamical Instability of a Doubly Quantized Vortex in a Bose-Einstein condensate.
Phys. Rev. Lett. 93, 160406 (2004)

T.A. Pasquini, Y. Shin, C. Sanner, M. Saba, A. Schirotzek, D.E. Pritchard, and W. Ketterle:
Quantum reflection of atoms from a solid surface at normal incidence.
Phys. Rev. Lett. 93, 223201 (2004).

T. Mukaiyama, J. R. Abo-Shaeer, K. Xu, J. K. Chin, and W. Ketterle:
Dissociation and Decay of Ultracold Sodium Molecules.
Phys. Rev. Lett. 92, 180402 (2004).

Y. Shin, M. Saba, A. Schirotzek, T.A. Pasquini, A.E. Leanhardt, D.E. Pritchard, and W. Ketterle:
Distillation of Bose-Einstein condensates in a double-well potential.

Phys. Rev. Lett. 92, 150401 (2004).

Y. Shin, M. Saba, T. Pasquini, W. Ketterle, D.E. Pritchard, and A.E. Leanhardt:
Atom interferometry with Bose-Einstein condensates in a double-well potential.
Phys. Rev. Lett. 92, 050405 (2004).

K. Xu, T. Mukaiyama, J.R. Abo-Shaeer, J.K. Chin, D. Miller, and W. Ketterle:
Formation of Quantum-Degenerate Sodium Molecules.
Phys. Rev. Lett. 91, 210402 (2003).

A.E. Leanhardt, T.A. Pasquini, M. Saba, A. Schirotzek, Y. Shin, D. Kielpinski, D.E. Pritchard, and W. Ketterle:
Cooling of Bose-Einstein condensates below 500 Picokelvin.
Science 301, 1513-1515 (2003).

J.K. Chin, J.M. Vogels, and W. Ketterle:
Amplification of Local Instabilities in a Bose-Einstein Condensate with Attractive Interactions.
Phys. Rev. Lett. 90, 160405 (2003).

A.E. Leanhardt, Y. Shin, D. Kielpinski, D.E. Pritchard, and W. Ketterle:
Coreless vortex formation in a spinor Bose-Einstein condensate.
Phys. Rev. Lett. 90, 140403 (2003).

A.E. Leanhardt, Y. Shin, A.P. Chikkatur, D. Kielpinski, W. Ketterle, and D.E. Pritchard:
Bose-Einstein condensates near a microfabricated surface.
Phys. Rev. Lett. 90, 100404 (2003).

J.M. Vogels, J. K. Chin, and W. Ketterle:
Coherent Collisions between Bose-Einstein Condensates.
Phys. Rev. Lett. 90, 030403 (2003).

A. Görlitz, T.L. Gustavson, A.E. Leanhardt, R. Löw, A.P. Chikkatur, S. Gupta, S. Inouye, D.E. Pritchard, and W. Ketterle:
Sodium Bose-Einstein Condensates in the F=2 State in a Large-volume Optical Trap. Phys. Rev. Lett. 90, 090401 (2003).

"Observation of Caustics in the Trajectories of Cold Atoms in a Linear Magnetic Potential", W. Rooijakkers, S. Wu, P. Striehl, M. Vengalattore and M. Prentiss
Phys. Rev. A 68, 063412 (2003).

"Ferromagnets for Integrated Atom Optics:, M. Vengalattore, R.S. Conroy, W. Rooijakkers, andM.Prentiss, J. Appl. Phys. 95 4404-4407 (2004).

"Bidirectional propagation of cold atoms in a "stadium"-shaped magnetic guide". S. Wu, W. Rooijakkers, P. Striehl, M. Prentiss, Phys. Rev. A 70, 013409 (2004).

"Dynamical instability of a doubly quantized vortex in a Bose-Einstein condensate", Y. Shin, M. Saba, M. Vengalattore, T.A. Pasquini, C. Sanner, A.E. Leanhardt, M. Prentiss, D.E. Pritchard, W. Ketterle. Phys. Rev. Lett. 93, 160406 (2004).

"Splitting matter waves using an optimized standing-wave light-pulse sequence", S. Wu, Y-J Wang, Q. Diot, M. Prentiss. Phys. Rev. A. 71, 43602 (2005).

"Atom Michelson interferometer on a chip using a Bose-Einstein condensate", Y-J Wang, D.Z. Anderson, W.M. Bright, E.A. Cornell, Q. Diot, T. Kishimoto, M. Prentiss, R.A. Saravanan, S.R. Segal, S. Wu. Phys. Rev. Lett. 94, 090405 (2005).

"Dissociation of ligand-receptor complexes using magnetic tweezers". C. Danilowicz, D. Greenfield and M. Prentiss. Anal. Chem. 77: 3023-3028 (2005).

"Interference of Bose-Einstein condensates split with an atom chip", Y. Shin, C. Sanner, G.-B. Jo, T.A. Pasquini, M. Saba, W. Ketterle, D.E. Pritchard, M. Vengalattore and M. Prentiss, Phys. Rev. A 72:021604 (2005).

A reciprocal magnetic trap for neutral atoms", M. Vengalattore and M. Prentiss, Eur. Phys. J. D 35:69-73 (2005).

"Time domain de Broglie wave interferometry along a magnetic guide", S. Wu, E.J. Su and M. Prentiss, Eur. Phys. J. D 35: 111-118 (2005).

Nonequilibrium coherence dynamics of a soft boson lattice A. K. Tuchman, C. Orzel, A. Polkovnikov, and M. A. Kasevich Phys. Rev. A 74, 051601 (2006).

Long-Term Stability of an Area-Reversible Atom-Interferometer Sagnac Gyroscope, D. S. Durfee, Y. K. Shaham, and M. A. Kasevich Phys. Rev. Lett. 97, 240801 (2006).

Ultrafast Electron Pulses from a Tungsten Tip Triggered by Low-Power Femtosecond Laser Pulses, P. Hommelhoff, C. Kealhofer, and M. A. Kasevich, Phys. Rev. Lett. 97, 247402 (2006).

Field emission tip as a nanometer source of free electron femtosecond pulses.
Hommelhoff, P; Sortais, Y; Aghajani-Talesh, A; Kasevich, M. A. Kasevich, Phys. Rev. Lett. 96,.077401/1-4 (2006).

High-order inertial phase shifts for time-domain atom interferometers, K. Bongs, R. Launay, and M. A. Kasevich, Appl. Phys. B 84, 599 (2006).

Sensitive Detection of Cold Cesium Molecules Formed on Feshbach Resonances, C. Chin, A.J. Kerman, V. Vuletic, and S. Chu, Phys. Rev. Lett. 90, 033201 (1-4) (2003).

Observation of Collective-Emission-Induced Cooling of Atoms in an Optical Cavity, H.W. Chan, A.T. Black, and V. Vuletic, Phys. Rev. Lett. 90, 063003 (1-4) (2003).

Observation of Collective Friction Forces due to Self-Organization of Atoms: From Rayleigh to Bragg Scattering, A.T. Black, H.W. Chan, and V. Vuletic, Phys. Rev. Lett. 91, 203001 (1-4) (2003).

Impact of Casimir-Potential and Johnson Noise on Bose-Einstein Condensate Stability near Surfaces, Y. Lin, I. Teper, C. Chin, and V. Vuletic, Phys. Rev. Lett. 92, 050404 (1-4) (2004).

Precision Feshbach Spectroscopy of Ultracold Cs2, C. Chin, V. Vuletic, A.J. Kerman, S. Chu, E. Tiesinga, P.J. Leo, and C.J. Williams, Phys. Rev. A 70, 032701 (1-13) (2004).

Collective forces on atoms in resonators, A.T. Black, J. K. Thompson, and V. Vuletic, J. Phys. B: At. Mol. Opt. Phys. 38, S605-S615 (special issue Einstein centennial year) (2005).

On-Demand Superradiant Conversion of Atomic Spin Gratings into Single Photons with High Efficiency, A.T. Black, J. K. Thompson, and V. Vuletic, Phys. Rev. Lett. 95, 133601 (1-4) (2005).

Number of Papers published in peer-reviewed journals: 68.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Wolfgang Ketterle:
New Frontiers with Ultracold Gases.
in: Atomic Physics 19, Proceedings of the XIX International Conference on Atomic Physics (ICAP) 2004, eds. L.G. Marcassa, K. Helmerson, V.S. Bagnato (American Institute of Physics, 2005) pp. 25-29.

Wolfgang Ketterle:
The Bose-Einstein Condensate- a Superfluid Gas of Coherent Atoms.
Proceedings of the XVIII International Conference on Atomic Physics (ICAP) 2002, eds. H.R. Sadeghpour, E.J. Heller, D.E. Pritchard (World Scientific, 2003) pp. 11-18.

Cooling of cesium atoms by collective emission inside an optical resonator, A.T. Black, H.W. Chan, and V. Vuletic, published in Proceedings of the XVIII. International Conference on Atomic Physics (ICAP 2002, Boston), edited by H. Sadeghpour, R. Heller, and D. Pritchard, pp.91-98, (World Scientific, Singapore 2003), invited presentation.

Controlled Atom-Molecule Interactions in Ultracold Gases, C. Chin, A.J. Kerman, V. Vuletic, and S. Chu, published in Proceedings of the second Asia Pacific Conference on Few-Body Problems in Physics (Shanghai 2002), Mod. Phys. Lett. A 18, pp. 398-401 (2003).

Self-Organization of Atomic Samples in Resonators and Collective Light Forces, A.T. Black, H.W. Chan, and V. Vuletic, published in Proceedings of the 16th International Conference on Laser Spectroscopy (ICOLS 2003, Palm Cove), edited by P. Hannaford, A. Sidorov, H. Bachor, and K. Baldwin, pp. 345-352 (World Scientific, Singapore 2004), invited presentation.

Atomic samples in resonators: forces, photons, feedback, J. K. Thompson, A.T. Black, and V. Vuletic, XIX. International Conference on Atomic Physics (ICAP 2004, Rio de Janeiro, 7/2004), edited by L. G. Marcassa, K. Helmerson, and V. S. Bagnato, pp. 175-183 (AIP Conference Proceedings, Melville, New York 2005), invited presentation.

S. Pötting, P. Meystre, and E. M. Wright, "Atomic solitons in optical lattices", in “Nonlinear Photonic Crystals”, edited by R. L. Slusher and B. Eggleton, Springer Verlag (2003).

B. P. Anderson and P. Meystre, “Nonlinear atom optics,” Contemporary Physics 44, 473 (2003).

Number of Papers published in non peer-reviewed journals: 8.00

(c) Presentations

Collective cavity cooling of cesium atoms, H.W. Chan, A.T. Black, and V. Vuletic,
New Laser Scientist Conference (Orlando 2002).

Collective-emission-induced cooling of atoms in a resonator, A.T. Black, H.W. Chan, and V. Vuletic, Optics and Electronics Seminar, Stanford University (2002).

Collective cavity cooling of cesium atoms, H.W. Chan, A.T. Black, and V. Vuletic,
Physics Colloquium, NYU (New York 2003).

Collective Friction Forces due to Self-Organization of Cesium Atoms: From Rayleigh to Bragg Scattering, A.T. Black, H.W. Chan, and V. Vuletic, 9th Japan-US Joint Seminar on Quantum Correlation and Coherence (Yatsugatake, Japan 2003).

Stability of Bose-Einstein condensates near room-temperature surfaces, Y. Lin, I. Teper, C. Chin, and V. Vuletic, Physics Colloquium, York University (Toronto 2003).

Collective laser cooling due to spatial self-organization of classical atoms: From Rayleigh to Bragg scattering, A.T. Black, H.W. Chan, and V. Vuletic, Physics Colloquium, University of Toronto (2003).

Collective Friction Forces due to Spatial Self-Organization of Atoms: From Rayleigh to Bragg Scattering, A.T. Black, J. Thompson, H.W. Chan, and V. Vuletic
Joint Atomic Physics Series, Harvard University (Cambridge 2/2004).

Collective laser cooling due to spatial self-organization of classical atoms: From Rayleigh to Bragg scattering, A.T. Black, J. Thompson, H.W. Chan, and V. Vuletic,
Physics Colloquium, University of Colorado (Boulder 3/2004).

Collective laser cooling due to spatial self-organization of classical atoms: From Rayleigh to Bragg scattering, A.T. Black, J. Thompson, H.W. Chan, and V. Vuletic,
Physics Colloquium, University of Wisconsin-Madison (4/2004).

Stability of Bose-Einstein condensates near room-temperature surfaces, Y. Lin, I. Teper, C. Chin, and V. Vuletic, Workshop on Mesoscopic Physics, Quantum Optics, and Quantum Information, Institute for Theoretical Atomic and Molecular Physics (ITAMP) (Cambridge 5/2004).

Collective laser cooling due to spatial self-organization of classical atoms: From Rayleigh to Bragg scattering, A.T. Black, J. Thompson, H.W. Chan, and V. Vuletic,
Workshop on Quantum Gases, Kavli Institute for Theoretical Physics, UC Santa Barbara (6/2004).

Bose-Einstein condensates near room-temperature surfaces, Y. Lin, I. Teper, C. Chin, and V. Vuletic, Boulder summer school on "Coherence and Interactions in Atomic and Condensed Matter Physics", University of Colorado (7/2004).

Collective atom-cavity interactions, J.K. Thompson, A. T. Black, and V. Vuletic,
Workshop on "Micro-cavities in Quantum Optics" (Ringberg, Germany, 9/2004).

Many-atom single-photon source, A. T. Black, J.K. Thompson, and V. Vuletic,
Atomic Physics Seminar, University of Connecticut, (10/2004).

Single photons from many atoms, A.T. Black, J.K. Thompson, and V. Vuletic,
IQEC/CLEO-PR2005 (Tokyo 7/2005).

Single photons, single atoms, and squeezed spins, I. Teper, Y. Lin, A.T. Black, J. Simon, J.K. Thompson, and V. Vuletic, EuroConference on Ultracold Gases and their applications, (San Feliu de Guixols, Spain, 9/2005).

Single photons stored in many entangled atoms, J.K. Thompson, J. Simon, A. T. Black, and V. Vuletic, Physics Colloquium, University of Chicago (11/ 2005).

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

“Laser cooling in anisotropic traps”, M. Vengalattore, R.S. Conroy, M. Prentiss. In: International Quantum Electronics Conference (IQEC). IEEE Cat. No. 04CH37598. Piscataway, NJ, IEEE, 2004, 2 pp.

“Simultaneous bidirectional propagation of cold atoms in a “stadium” shaped magnetic waveguide ring”, S. Wu, P. Striehl, W. Rooijakkers, M. Prentiss. In: International Quantum Electronics Conference (IQEC). IEEE Cat. No. 04CH37598. Piscataway, NJ, IEEE, 2004, 3 pp.

“Optical beam splitter integrated on a magnetic atom chip”, D. Diot, Y-J Wang, D.Z. Anderson, E.A. Cornell, R.A. Saravanan, V.M. Bright, M. Prentiss. . In: International Quantum Electronics Conference (IQEC). IEEE Cat. No. 04CH37598. Piscataway, NJ, IEEE, 2004, 1 pp.

“Guiding of light in an ultracold, anisotropic medium”, M. Vengalattore and M. Prentiss, in 2005 Quantum Electronics and Laser Science Conference (QELS) (IEEE Cat. No. 05CH37696), Vol 1. Piscataway, NJ, USA: IEEE, 2005. p. 482-483.

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

(d) Manuscripts

Number of Manuscripts: 0.00

Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED
Hilton Chan	1.00
Adam Black	1.00
Dennis Douglas	1.00
Bennet Kalafut	1.00
Omijyoti Dutta	1.00
Hermann Uys	1.00
Dominic Meiser	1.00
Igor Teper	1.00
Yu-ju Lin	1.00
Catherine Kealhoffer	1.00
Saijun Wu	0.50
Jonathan Gillen	1.00
Wei Li	0.50
Mingchang Liu	0.50
Yong-Il Shin	0.50
Thomas Pasquini	0.50
Gyu-boong Yo	0.50
Aaron Leanhardt	0.50
Ananth Chikkatur	0.50
Ruquan Wang	0.50
HuiChun Chen	0.50
Shengwey Chiow	1.00
FTE Equivalent:	**17.00**
Total Number:	**22**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Peter Hommelhoff	1.00
Gary Zabow	1.00
Pablo Londero	0.60
Michele Saba	0.30
Markku Jaaskelainen	1.00
Takahiko Miyakawa	1.00
FTE Equivalent:	**4.90**
Total Number:	**6**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Pierre Meystre	0.10	No
Roy Glauber	0.10	Yes
Ewen Wright	0.10	No
Mark Kasevich	0.10	No
Vladan Vuletic	0.10	No
Wolfgang Ketterle	0.10	Yes
David Pritchard	0.10	Yes
Mara Prentiss	0.10	No
FTE Equivalent:	**0.80**	
Total Number:	**8**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME	
Ruquan Wang	
Aaron Leanhardt	
Jamil Abo-Shaeer	
Yong-Il Shin	
Adam Black	
Ari Tuchman	
Total Number:	**6**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

FINAL REPORT: Strategic Applications of Ultracold Atoms
Consortium members; Arizona, Harvard, MIT, Stanford

Table of Contents

Statement of Problem Studied

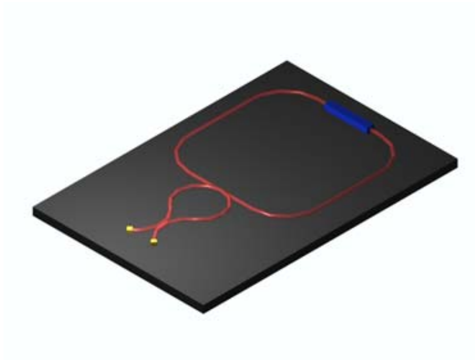


Fig. 1. Atom laser gyro (ALG). An active atom laser gain element (blue) injects coherent de Broglie waves into 10 cm x 10 cm microfabricated ring resonator (red) and a planar substrate (black). Atom detection (yellow) is at the Heisenberg limit using quantum state manipulation techniques.

This consortium proposes a focused collaborative program to advance matter wave sensors. We want to combine atom interferometry with atom lasers and atom waveguides with the prospect of improving the sensitivity of such sensors by orders of magnitude as compared with existing state-of-the-art sensors. We will identify, explore and exploit fundamental scientific possibilities surrounding the production, manipulation and detection of ultra-cold atoms for a variety of sensing applications. Such sensors include gravimeters, gravity gradiometers, gyroscopes, magnetometers and frequency standards and have applications in science and technology and within the DoD.

Sensitive and accurate inertial force sensors can be used in covert/passive navigation, precision guidance, underground structure detection, gravitational mapping, *etc.* They are non-emanating and capable of operating in a jammed-GPS environment.

The recent demonstration of atom lasers and the recent progress in atom optics/interferometry raise the tantalizing prospect of a new class of ultra-sensitive sensors drawing on advances in both areas (Figs. 1 and 2). Compact, field-ready versions of these sensors could be orders of magnitude more sensitive than current state-of-the-art sensors.

As a concrete example of how developments in the atom laser and atom optics/interferometry fields will impact sensor technology, we consider the impact of advances in atom source, atom optics and atom readout on precision rotation sensing. Fig. 1 illustrates our vision of a prototype Sagnac effect rotation sensor, an atom-laser gyroscope. We want to emphasize that *all* components described below have already been demonstrated or are under development in at least one of the collaborating groups. The device operating principles are as follows: Single mode atom waveguides are used to guide atoms in a ring resonator configuration (analogous to the resonator of a ring laser gyroscope). An active atom gain element is inserted in the ring to inject de Broglie waves into the ring. Atoms are outcoupled at a waveguide beamsplitter and mixed on an atom-heterodyne detector. Squeezed state detection techniques are used to detect rotation shifts below the shot-noise limit. Spurious interferometer phase shifts, due to atom-atom interactions, are suppressed by tuning the atom-atom interaction strength to zero using Feshbach resonances. Intracavity loss from three-body collisions and output coupling of atoms is compensated for by the active gain element. To estimate the possible performance of this device, we assume that 10^6 atoms/sec can be coherently coupled into the ring through the active gain element and then detected at the Heisenberg-limit, that the ring has an area of 100 cm^2 (for a 10 cm x 10 cm device), and that an atom transits the loop an average of 10 times before being outcoupled. In this case, the device can resolve rotations of $2x10^{-15}$ rad/sec after 1 second. This is a factor of 10^6 improvement over the current state-of-the-art.

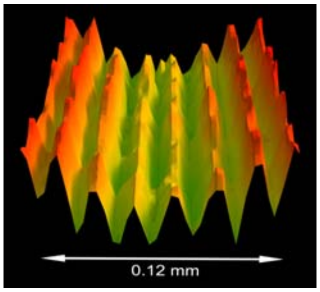


Fig 2. Interference fringes of two overlapping Bose-Einstein condensates. A major goal of the consortium is to develop this first demonstration into high-precision matter-wave sensors. This will be done by combining state-of-the art atom interferometry, BEC atom sources and atom wave guides.

Minor modifications in the waveguide topologies allow for the realization of compact acceleration sensors such as gravimeters and gravity gradiometers, with similar gains in sensitivity expected. Assumptions similar to those of the previous paragraph lead to estimated accelerometer sensitivities of 10^{-14} g in 1 second and sensitivities to gravity gradients of 10^{-3} E (1 E = 10^{-9} sec^{-2}) after 1 second.

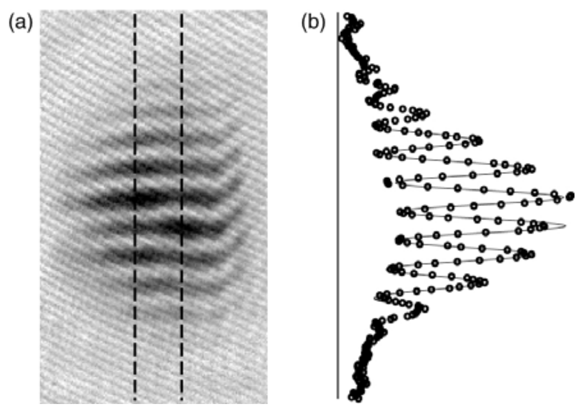
Summary of most important results

Major program accomplishments are summarized below.

BEC Interferometery (Prichard/Ketterle; MIT):
Atom interferometry with Bose-Einstein condensates in a double-well potential

The applicability, accuracy, and sensitivity of atom interferometers may be improved by exploiting the laser-like coherence properties of gaseous Bose-Einstein condensates in combination with the fine manipulation capabilities of atomic microtraps and waveguides. Current proposals for microtrap and waveguide interferometers utilize double-well potentials for beam splitters and recombiners. To implement a prototype of such schemes, we created a trapped-atom interferometer using gaseous Bose-Einstein condensates coherently split by deforming an optical single-well potential into a double-well potential [1].

Sodium condensates were split by deforming an initially single-well potential into two wells separated by 13 μm. To avoid deleterious mean field effects common to traditional in-trap recombination schemes, the relative phase between the two condensates was determined from the spatial phase of the matter wave interference pattern formed upon releasing the atoms from the separated potential wells. The coherence time of the separated condensates was measured to be 5 ms, and was set by technical limitations of our current setup. The large separation between the split potential wells allowed the phase of each condensate to evolve independently and either condensate to be addressed individually.

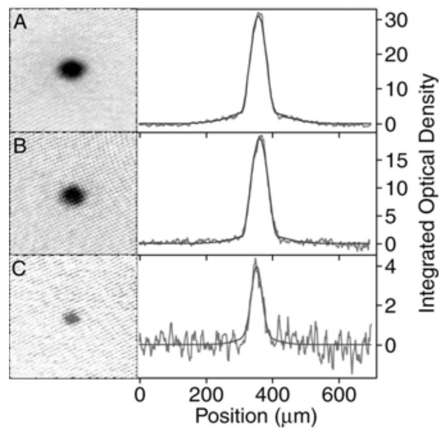


Matter wave interference. (a) Absorption image of condensates released from the optical double-well potential and allowed to expand for 30 ms. The field of view is 600 μm × 350 μm. (b) Radial density profiles were obtained by integrating the absorption signal between the dashed lines, and typical interference patterns had > 60% contrast. The spatial phase of the matter wave interference pattern was extracted from the fit shown.

Cooling of Bose-Einstein condensates below 500 Picokelvin

The lowest temperatures for trapped atoms are usually achieved in low-density samples. At high densities, interaction effects adversely affect the cooling process and the temperature diagnostics. We have achieved a new record-low temperature of less than 500 picokelvin in a very weak trap using a combination of gravitational and magnetic forces [2]. The partially condensed atomic vapors were adiabatically decompressed by weakening the gravito-magnetic trap to a mean frequency of 1 Hertz, then evaporatively reduced in size to 2500 atoms. This lowered the peak condensate density to 5×10^{10} atoms per cubic centimeter and cooled the entire cloud in all three dimensions to a kinetic temperature of 450 ± 80 picokelvin.

These samples are characterized by a thermal velocity of 1 mm/s, a speed of sound of 100 μm/s, and a healing length limited by the 20 μm harmonic oscillator length of the trapping potential. Low temperature and low-density ensembles are important for spectroscopy, metrology, and atom optics. In addition, they are predicted to experience quantum reflection from material surfaces.

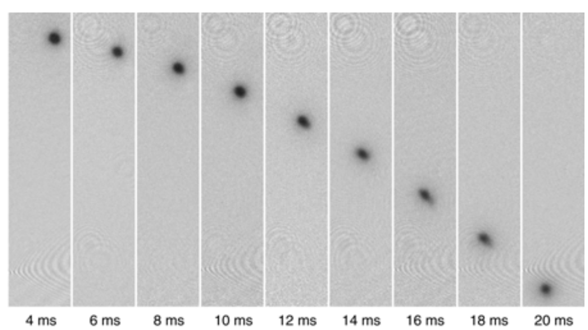


Picokelvin temperature thermometry. Partially condensed atomic vapors confined in the gravito-magnetic trap with (A) 28,000, (B) 16,000, and (C) 2,500 atoms. The one-dimensional cross sections (red) were obtained by integrating the two-dimensional absorption images of the trapped clouds along the y-axis. Bimodal fits (blue) yielded temperatures of (A) 1.05 ± 0.08 nK, (B) 780 ± 50 pK, and (C) 450 ± 80 pK, where the uncertainty is due to the fit of an individual image. The field of view for the absorption images in (A) to (C) is 460 μm x 460 μm.

Formation of Quantum-Degenerate Sodium Molecules

A current frontier in the field of ultracold gases is the study of ultracold molecules. In 2003, several groups succeeded in converting ultracold atoms into ultracold molecules by magnetically tuning a molecular level close to zero binding energy (Feshbach resonance). Atoms can then form molecules without release of heat.

In our experiment, we produced ultracold sodium molecules from an atomic Bose-Einstein condensate by ramping an applied magnetic field across a Feshbach resonance [3]. More than 10^5 molecules were generated with a conversion efficiency of ~4%. High phase-space density could only be achieved by rapidly removing residual atoms, before atom-molecule collisions caused trap loss and heating. This was accomplished by a new technique for preparing pure molecular clouds, where light resonant with an atomic transition selectively ‘‘blasted’’ unpaired atoms from the trap. Time-of-flight analysis of the pure molecular sample yielded an instantaneous phase-space density greater than 20.

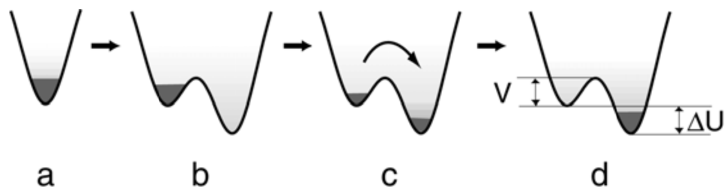


Ballistic expansion of a pure molecular sample. Absorption images of molecular clouds (after reconversion to atoms) are shown for increasing expansion time after switching off the optical trap. The small expansion velocity corresponds to a temperature of about 30 nK, characteristic of high phase-space density. The images are taken along the weak axis of the trap. The field of view of each image is 3.0 mm x 0.7 mm.

Distillation of Bose-Einstein condensates in a double-well potential

The characteristic feature of Bose-Einstein condensation is the accumulation of a macroscopic number of particles in the lowest quantum state. Condensate fragmentation, the macroscopic occupation of two or more quantum states, is usually prevented by interactions [4]. However, multiple condensates may exist in metastable situations. Let's assume that an equilibrium condensate has formed in one quantum state, but now we modify the system allowing for one even lower state. How does the original condensate realize that it is in the wrong state and eventually migrate to the true ground state of the system? What determines

the time scale for this equilibration process? This is the situation, which we have experimentally explored by preparing a Bose-Einstein condensate in an optical dipole trap and distilling it into a second empty dipole trap adjacent to the first one [5]. The distillation was driven by thermal atoms spilling over the potential barrier separating the two wells and then forming a new condensate. This process serves as a model system for metastability in condensates, provides a test for quantum kinetic theories of condensate formation, and also represents a novel technique for creating or replenishing condensates in new locations.



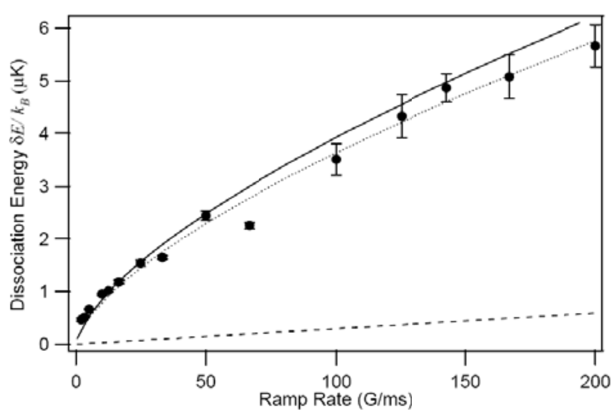
Scheme for distillation of condensates in a double-well potential. (a) Condensates are loaded into the left well. (b) A new ground state is created by linearly ramping the trap depth of the right well from zero to the final value. (c) Atoms transfer into the right well via high-energy thermal atoms, and a new condensate starts to form in the right well. (d) The whole system has equilibrated.

Dissociation and Decay of Ultracold Sodium Molecules

We have studied the dissociation and decay of ultracold molecules. Sodium molecules were formed in a highly excited vibrational state by recombining two ultracold atoms [5]. An external magnetic field “tuned” the molecular binding energy close to zero (Feshbach resonance) allowing resonant recombination.

By ramping up the magnetic field, the molecular level was moved into the continuum, and the molecule dissociated. When the magnetic field ramp is very slow, the molecules follow adiabatically and end up in the lowest energy state of the atoms. The dissociation products will populate higher-lying atomic states if the ramp is fast (compared to the strength of the coupling between the molecular and atomic states). Therefore, from the observed dissociation energies, the strength of the atom-molecule coupling could be determined.

The non-linear dependence of the dissociation energy on the ramp speed reflects the Wigner threshold law for the onset of dissociation: The dissociation lifetime decreases when the molecular energy is higher above threshold. Furthermore, inelastic molecule-molecule and molecule-atom collisions were characterized. The rapid inelastic decay imposes a severe limit to further evaporative cooling.



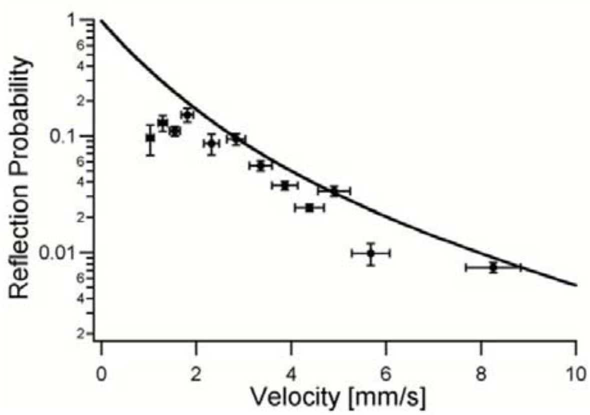
Dissociation energy of sodium molecules as a function of magnetic field ramp rate. The dashed line represents a theoretical prediction of a linear relation, the solid line shows the result of our theory with no free parameters (using a theoretical value for the width ΔB of the Feshbach resonance), and the dotted line shows a curve with ΔB as a fitting parameter.

Quantum reflection of ultracold atoms from a solid surface

Quantum reflection is a process in which a particle reflects from a potential without reaching a classical turning point. Quantum reflection requires low incident velocity or weak attraction to the surface, conditions previously realized only using liquid helium surfaces or solid surfaces at grazing incidence [6].

In this work, we demonstrated quantum reflection of ultracold sodium atoms from a solid silicon surface at normal incidence [7].

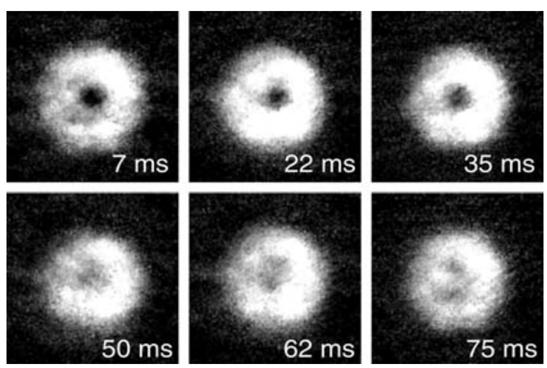
Using Bose-Einstein condensates in a weak gravitomagnetic trap to reduce the atomic motion, atoms were incident on the surface at velocities as low as 1 mm/s, corresponding to collision energies of $k_B \times 1.5$ nanokelvin. Reflectivities of 20% are in qualitative agreement with theoretical predictions. When atoms were confined in one dimension by a silicon surface, lifetime measurements indicate reflection probabilities in excess of 50%. If higher reflectivities can be obtained with low-density of thinned surfaces, new atom-optical elements based on normal reflection will become possible.



Reflection probability vs incident velocity. The solid curve is a numerical calculation for individual atoms incident on a conducting surface.

Dynamical Instability of a Doubly Quantized Vortex in a Bose-Einstein condensate

The study of topological excitations and their stability is an active frontier in the field of quantum degenerate gases. Most studies focused on vortices with one quantum of circulation. In earlier work, we created doubly quantized vortices in a Bose-Einstein condensate [8], but due to technical limitation, could not observe the predicted decay . Now we have studied the time evolution of a doubly quantized vortex state [9] and directly confirm its dynamical instability by observing that a doubly-quantized vortex core splits into two singly-quantized vortex cores [10]. The characteristic time scale of the splitting process was determined as a function of atom density and was longer at higher atomic density. The vortices were topologically imprinted into the condensate by reversing the magnetic field which created topological phases.

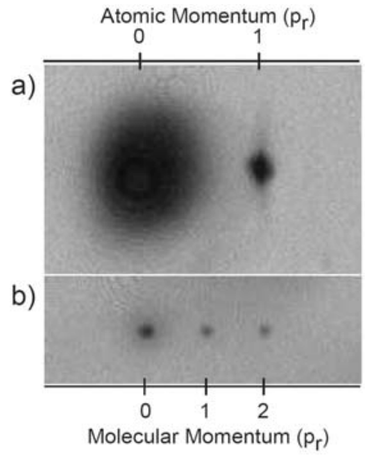


Decay of a doubly quantized vortex. Axial absorption images of condensates after 15 ms of ballistic expansion with a variable hold time after imprinting a doubly quantized vortex. A doubly quantized vortex decayed into two singly quantized vortices. The field of view in each image is 320 µm × 320 µm.

Coherent Molecular Optics using Sodium Dimers

Coherent molecular optics was performed using two-photon Bragg scattering. [11] Molecules were produced by sweeping an atomic Bose-Einstein condensate through a Feshbach resonance [3]. Using

optical standing waves of suitably chosen frequencies, sodium dimers were coherently manipulated with negligible heating or other incoherent processes. The spectral width of the molecular Bragg resonance which is Doppler sensitive corresponded to an instantaneous temperature of 20 nK, indicating that atomic coherence was transferred directly to the molecules. An autocorrelating interference technique was used to observe the quadratic spatial dependence of the phase of an expanding molecular cloud. Finally, atoms initially prepared in two momentum states were observed to crosspair with one another, forming molecules in a third momentum state. This process is analogous to sum-frequency generation in optics.

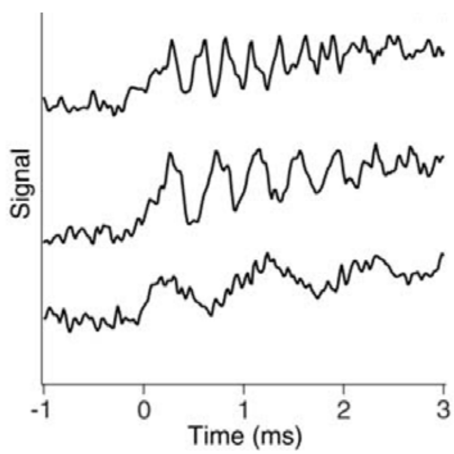


Sum frequency generation of atomic matter waves. (a) Atoms were initially prepared in momentum states 0, 1. (b) By sweeping through the Feshbach resonance, atoms combine to form molecules with momenta 0, 1, and 2. Momentum state 1 is the sum frequency of the two atomic matter waves. The "nonlinear medium" is provided by the atomic interactions. The time-of-flight in each image is 17 ms.

Continuous measurement of the relative phase of two Bose-Einstein condensates using light scattering

We have demonstrated an experimental technique based on stimulated light scattering to continuously sample the relative phase of two spatially separated Bose-Einstein condensates of atoms [Saba, 2005 #1414]. This is the first time that the phase of a condensate could be determined in a non-destructive way. The phase measurement process created a relative phase between two condensates with no initial phase relation, read out the phase, and monitored the phase evolution.

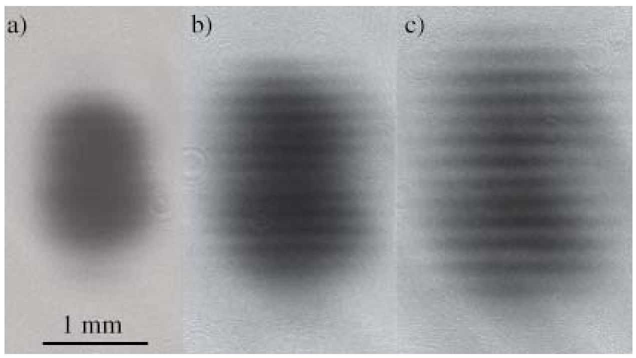
By monitoring the phase of two condensates at two separated times, interferometry between two trapped Bose-Einstein condensates without need for splitting or recombining.



Continuous optical read-out of the relative phase of two condensates. The traces show that the intensity of the light scattered from the condensates oscillates in time. Bragg scattering starts at t =0 when the second beam is turned on. The relative depth of the two wells was different for the three traces, generating a difference in the beat frequency between the two condensates.

High-Contrast Interference in a Thermal Cloud of Atoms

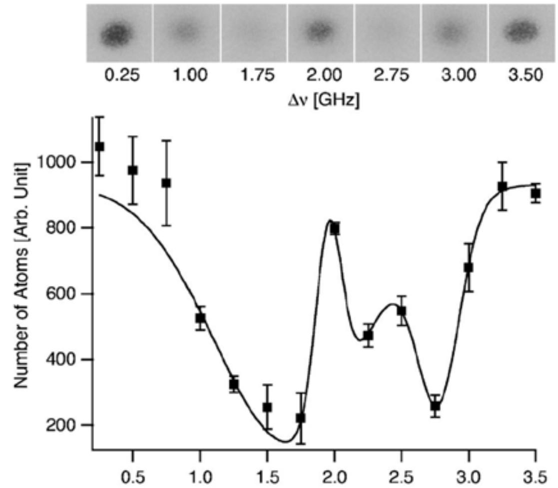
Currently, there is considerable interest in characterizing the coherence properties of non-condensed systems including ultracold fermions, fermion pairs, and ultracold molecules. We have used an interferometric autocorrelation technique, previously applied only to condensates [12] to study the coherence properties of an alkali gas at finite temperature [13]. Bragg diffraction was used to create two spatially separated wave packets, which would interfere during expansion, analogous to a Young's double slit experiment. Fringe visibility greater than 90% was observed in a thermal cloud. We have shown that interference is lost when the separation between the wave packets exceeds the coherence length. However, the coherence length grows during ballistic expansion, and can become arbitrarily large. This can be understood by the conservation of local phase-space density, where the decrease in density is accompanied by a decrease in momentum spread. When the sample was filtered in momentum space using long, velocity-selective Bragg pulses, the contrast was enhanced; an effect the simple theory of a non-interacting gas could not account for.



Contrast emerged as the coherence length grew in ballistic expansion. The initial cloud separation was 2 μm, and the expansion times were 14 ms, 20 ms and 25 ms, respectively.

Sodium Bose-Einstein Condensates in an Optical Lattice

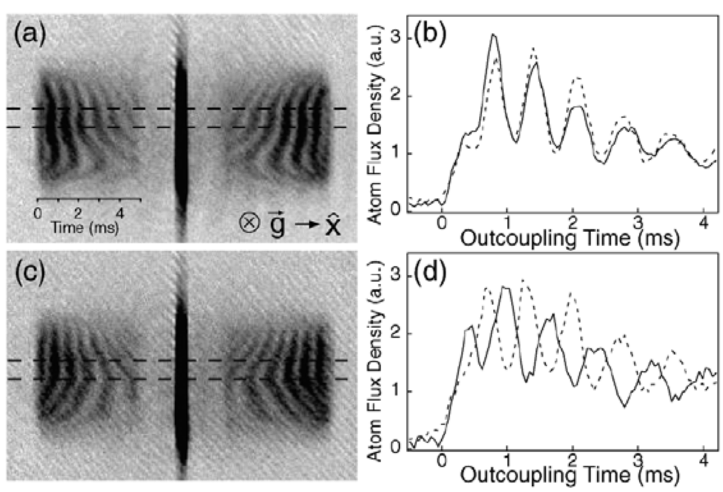
Optical lattices have become a powerful tool to enhance the effects of interaction in ultracold atomic systems to create strong correlations and probe many-body physics beyond the mean-field theory [14]. Simply through varying the depth of the lattice potential, one changes the tunneling rate as well as the on-site interaction energy by changing the confinement of the atoms. So far, most optical lattice experiments have been performed with relatively heavy atomic species (e.g. rubidium and potassium) for which the recoil frequencies are lower and lasers are readily available to achieve trap depths of several tens of recoil frequencies at a few tens of milliwatts. For ^{23}Na, high power single-mode lasers are necessary for similar experiments. In this work, we chose to use a dye laser red-detuned by 5 nanometers from the D lines of sodium (589 nm). The spontaneous scattering rate limited the time window of the experiment to less than 50 ms, but was still sufficient to satisfy the adiabaticity condition to explore the quantum phase transition from a superfluid to a Mott insulator [15]. We also observed strong atom losses at various lattice laser detunings, which were interpreted as photoassociation transitions. The particular molecular states responsible for these transitions were identified through theoretical calculations and previous experimental data.



Photoassociation resonances: Atom loss from the optical lattice as a function of the lattice laser detuning. The top row of images shows the remaining atom cloud after the lattice was turned off and the cloud expanded for 30 ms. The lower graph shows the remaining number of atoms for these and additional frequency points. The zero of the *x* axis corresponds to a laser wavelength ofv594.490 nm.

Optical Weak Link between Two Spatially Separate Bose-Einstein Condensates

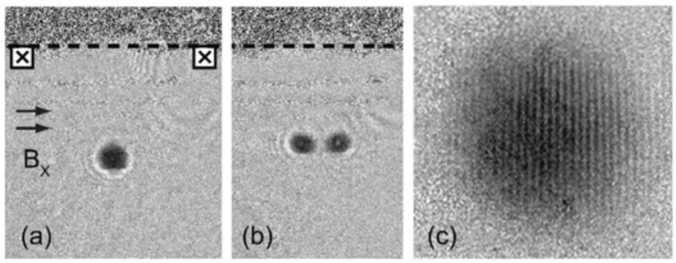
The concept of Josephson coupling can be extended to include two *spatially separate* quantum systems by using intermediate coupling systems. The phase of the coupling may be actively controlled by adjusting the coupling states of the intermediate systems. We have experimentally demonstrate phase-sensitive optical coupling of two spatially separate Bose- Einstein condensates using Bragg scattering [16]. We have studied two condensates in an optical double-well potential, irradiated by two pairs of Bragg beams which couple out beams of atoms propagating to the left or the right, respectively, and these unconfined propagating atoms constitute the intermediate coupling system in our scheme. Depending on the relative phases of the two condensates and the coupling states, we observe only one outcoupled beam propagating to one or the other side, or two identical beams propagating in opposite directions (see figure). This demonstrates phase control of currents and establishes a new scheme to realize Josephson effects with two non-overlapping condensates.



Symmetric and antisymmetric correlation between outcoupled atom patterns. Two pairs of Bragg beams outcoupled atoms in either +x or -x direction. Absorption images were taken after 5 ms outcoupling and 2 ms additional ballistic expansion. The left outcoupled atom patterns were compared with the corresponding right patterns. Depending on the frequency of the Bragg beams, we observed symmetric correlation between the two patterns (top) or antisymmetric correlations (bottom). The field of view is 0. 9 mm x 0.6 mm.

Interference of Bose-Einstein condensates split with an atom chip

A major step towards compact matter wave sensors is an atom interferometer on an atom chip. We have used an atom chip to split a single Bose-Einstein condensate of sodium atoms into two spatially separated condensates [17]. Dynamical splitting was achieved by deforming the trap along the tightly confining direction into a purely magnetic double-well potential. We observed the matter wave interference pattern formed upon releasing the condensates from the microtraps. The intrinsic features of the quartic potential at the merge point, such as zero trap frequency and extremely high field-sensitivity, caused random variations of the relative phase between the two split condensates. Moreover, the perturbation from the abrupt change of the trapping potential during the splitting was observed to induce vortices.



Splitting of condensates. (left) Condensates were initially loaded and prepared in the bottom well and (middle) split into two parts by increasing the external magnetic field. For clarity, two condensates were split by 80 μm. The dashed line indicates the chip surface position. (right) Two condensates were released from the magnetic double-well potential and the matter wave interference pattern of two condensates formed after time-of- flight.

Guided atom inteferometery (Prentiss, Harvard)

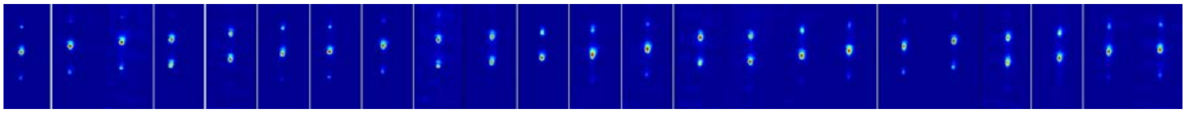
Before this project, it was not known whether the magnetic field confinement would destroy the coherence making guided atom rotation sensors impossible. We demonstrated that atoms confined in magnetic waveguides can retain external state coherence for times longer than 30 ms. In collaboration with the Cornell/Anderson group at JILA we showed that a BEC in a single waveguide mode can retain its coherence. In the Prentiss group, we demonstrated that a thermal atom sample occupying thousands of waveguide modes can still show a strong phase coherent interferometric signal at interrogation times of 30 ms. We have also shown continuous loading rates into magnetic waveguides that exceed 108 atoms per second, with pulsed rates that are orders of magnitude higher.

Waveguide atom interferometers offer great potential for creating small, compact, robust rotation and acceleration sensors for guidance applications. Right now, magnetic field guiding is the leading candidate for realizing such guided interferometers. The Harvard group has developed waveguides based on ferromagnetic material, that allow very tight confinement to be obtained far above the physical surface of the magnetic structure, greatly reducing the heating of the atoms and even destruction of the atom sample that has resulted in experiments using atom waveguides based on current flowing through microfabricated wires. These structures have been used to produce atom clouds longer that 2 cm with more than 10^9 trapped atoms.

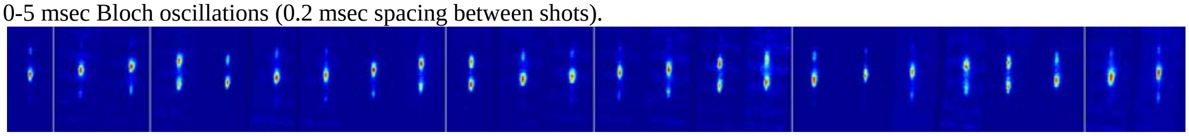
Waveguide BEC (Chu, Vuletic; MIT, Stanford):

We created quantized spin gratings by single-photon detection and convert them on demand into photons with retrieval efficiencies exceeding 40% (80%) for single (a few) quanta. We showed that the collective conversion process, proceeding via superradiant emission into a moderate-finesse optical resonator, required phase matching. The observed storage time of 3 s in the cold-atom sample, as well as the peak retrieval efficiency, are likely limited by Doppler decoherence of the entangled state.

We studied resonator-induced light forces arising from cooperative atom-light interaction. For such collective processes, the force on the sample can be orders of magnitude larger than the sum of conventional light forces on individual atoms. Since resonator-induced light forces can be dissipative even when the incident light is far detuned from atomic transitions, they may be applicable to target particles with a complex level structure.



0-5 msec Bloch oscillations (0.2 msec spacing between shots).



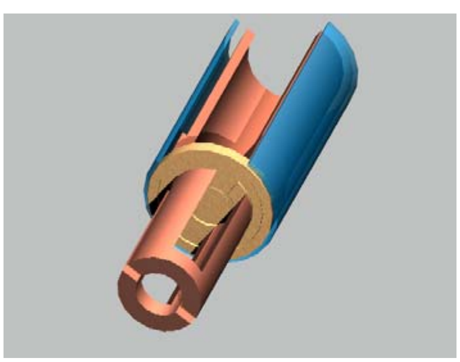
10-15 msec Bloch oscillations (0.2 msec spacing between shots)
Growth in width of the central peak is due to quantum phase diffusion of a coherent state in the mean field. This effect, established theoretically in 1997 for BEC sources, has not been observed for large ensembles of atoms prior to this work, and sets a fundamental limit on coherence time for BEC interferometry.

Bose-Einstein condensation has recently been achieved in a novel microchip topology. The experimental method to obtain BEC is robust and simple; it uses only a single vacuum chamber and a magnetic microtrap which is directly loaded from a standard magneto-optical trap. The short evaporation time of 3s is limited only by the axial trap vibration frequency, and it is estimatee that the evaporation time can be shortened to 1s at a MOT loading time of 500ms. The condensates containing a few thousand rubidium atoms are produced at a distance of 60 m from the silicon substrate, and are stable to distances down to 15 m. An atom number shot noise-limited imaging system for the condensate has been set-up to study the condensate. In the near future, we will try to demonstrate sub-shot noise fluctuations (“squeezing”) in the relative atom number contained in different spatial regions of the condensate. This is equivalent to a determination of the average condensate position with sub-shot noise accuracy, and may be of use in simple interferometric schemes with condensates.

Squeezing and quantum state control in optical lattices (Kasevich; Stanford):

We showed how mean field interactions can be exploited to balance variations in an external potential which might otherwise impair sensor performance. The basic idea is that the mean field enforces a balanced chemical potential, thus smoothes any inhomogeneity in the external confining potentials. We exploited this to measure, for the first time, quantum limited dephasing of a macroscopically populated state (number of particles ~ 100), and to demonstrate the dependence of this dephasing on atom number and number and the particle statistics of the initial state (see Fig.). This work shows that for a large class of initial conditions, coherence time in BEC sensor is limited to about 10 msec. In the process of this work, we discovered a sharp, thermally driven phase transition associated with the long range coherence properties of the system. Further investigation of this transition has indicated that this is likely a Kosterlitz-Thouless type transition.

We demonstrated and characterized a novel miniaturized trap for evaporative cooling of Li. Using this system, we achieved phase space densities above the BEC threshold for the difficult to cool Li isotope. The demonstrated trap dissipates on 7W of electrical power while tightly confining atoms at high density. The trap involves integration of a direct-bond copper chip (which is capable of very high current densities) with a 3 dimensional magnetic trapping structure.



Schematic illustration of the demonstrated mini-trap.

Theory (Meystre, Glauber, Wright; Tuscon/Harvard):

The theory collaboration has significantly advanced the state-of-knowledge for the quantum field theory of degenerate bosonic and fermionic systems, with particular emphasis to sensors applications. Most recently, the focus on fermionic systems may identify mitigation strategies to overcome some of the technology hurdles identified in the study of guided atom systems.

For example, it is only recently that it has been convincingly argued that atomic four-wave mixing is possible with fermions. However, the theory so as been limited to an incident beam consisting of a single test particle. It also neglected the dynamics of the density grating. These limitations have now been removed by taking into account both a multi-particle beam and the back-action of the incident beam on the fermionic density grating. Using this formalism, it has been shown that when the number of atoms in the incident beam becomes a sizable fraction of the number of atoms forming the density grating, it no longer decays away due to the dephasing resulting from the slightly different energies of the fermions forming the incident beam. Instead, it exhibits large nonlinear amplitude oscillations that are coupled to the Bragg oscillations of the beam. This leads to the efficient generation of the fourth scattered wave, even for times much longer than the grating dephasing time. It is well known that four-wave mixing with bosons can lead to the generation of squeezed states. Therefore a central feature of future work will examine the statistical properties of the scattered beam generated in fermionic four-wave mixing to see if it is possible to generate novel fermionic states. Phase conjugation should also be possible if one uses a superfluid Fermi gas due to the presence of anomalous moments resulting from the formation of Cooper pairs.

In related work, the phase resolution limit of a Mach-Zehnder atom interferometer whose input consists of degenerate quantum gases of either bosons or fermions has been analyzed. For degenerate gases, the number of atoms within one de Broglie wavelength is larger than unity, so that atom-atom interactions and quantum statistics are no longer negligible. It has been shown that for equal atom numbers, the phase resolution achievable with fermions can be noticeably better than for interacting bosons. This is a strong argument for a further extensive study of fermionic atom optics.

The recent experimental success in creating quantum-degenerate atomic Fermi gases is opening up fascinating new opportunities to explore the quantum statistics of ultracold atoms. Fermionic behavior is strongly constrained by the Pauli Exclusion Principle. This limits the variety of possible nonlinear atom optics effects, but also offers the potential for novel applications without analogs in optics. These include, for example, low-noise inertial and rotation sensors, and quantum information processing. In a new development of the theory research program, the new situation where a gas of bosons serves as a nonlinear medium for fermionic atoms has been explored. In particular, interatomic interaction between a Bose-Einstein condensate and a fermionic beam can be employed to manipulate the quantum state of the beam. As a first step, and drawing on an analogy to nonlinear optics, the interaction can be described in terms of an effective attractive Kerr nonlinearity, and show that a two-fermion bound state can result with a unique signature in a nonlinear atom optical experiment. Future study of this coupled Bose-Fermi systems may be of particular relevance for the manipulation of the quantum statistical properties of fermionic atomic beams, e.g. changes from antibunched and bunched beams, dynamic Cooper pairing, and the formation of quantum solitons in ultracold fermionic atomic beams.

We studied the possibility of inhibiting three-body recombination in atomic Bose-Einstein condensates via the application of resonant 2 pi laser pulses. These pulses result in the periodic change in the phase of the molecular state by pi , which leads to destructive interference between the decay amplitudes following successive pulses. We show that the decay rate can be reduced by several orders of magnitude under realistic conditions.

We studied the quantum dynamics of a two-mode Bose-Einstein condensate in a time-dependent symmetric double-well potential using analytical and numerical methods. The effects of internal degrees of freedom on the visibility of interference fringes during a stage of ballistic expansion are investigated varying particle number, nonlinear interaction sign and strength, as well as tunneling coupling. Expressions for the phase resolution are derived and the possible enhancement due to squeezing is discussed. In particular, the role of the superfluid-Mott insulator crossover and its analog for attractive interactions is recognized.

We described a matter-wave amplifier for vibrational ground-state molecules which uses a Feshbach resonance to first form quasibound molecules starting from an atomic Bose-Einstein condensate. The quasibound molecules are then driven into their stable vibrational ground state via a two-photon Raman transition inside an optical cavity. The transition from the quasibound state to the electronically excited state is driven by a classical field. Amplification of ground state molecules is then achieved by using a strongly damped cavity mode for the transition from the electronically excited molecules to the molecular ground state.

We investigated the potential of the so-called cross-correlation frequency-resolved optical gating (XFROG) technique originally developed for ultrashort laser pulses for the recovery of the amplitude and

phase of the condensate wave function of a Bose-Einstein condensate. Key features of the XFROG method are its high resolution, versatility, and stability against noise and some sources of systematic errors. After showing how an analog of XFROG can be realized for Bose-Einstein condensates, we illustrate its effectiveness in determining the amplitude and phase of the wave function of a vortex state. The impact of a reduction of the number of measurements and of typical sources of noise on the field reconstruction are also analyzed.

We briefly reviewed some recent developments in nonlinear atom optics. Basic principles, as well as some of the early effects predicted and observed in the nonlinear optics of bosonic atoms, are presented in general terms. Recent results on fermionic four-wave mixing and on the matter-wave analogue of optical second-harmonic generation are discussed in detail.

We propose a coherent beam splitter for polarized heteronuclear molecules based on a stimulated Raman adiabatic passage scheme that uses a tripod linkage of electrotranslational molecular states. We show that for strongly polarized molecules the rotational dynamics imposes significantly larger Rabi frequencies than would otherwise be expected, but within this limitation, a full transfer of the molecules to two counterpropagating ground-state wave packets is possible.

We considered the photoassociation of a low-density gas of quantum-degenerate trapped fermionic atoms into bosonic molecules in a spherically symmetric harmonic potential. For a dilute system and the photoassociation coupling energy small compared to the level separation of the trap, only those fermions in the single shell with Fermi energy are coupled to the bosonic molecular field. Introducing a collective pseudospin operator formalism we show that this system can then be mapped onto the Tavis-Cummings Hamiltonian of quantum optics, with an additional pairing interaction. By exact diagonalization of the Hamiltonian, we examine the ground state and low excitations of the Bose-Fermi system, and study the dynamics of the coherent coupling between atoms and molecules. In a semiclassical description of the system, the pairing interaction between fermions is shown to result in a self-trapping transition in the photoassociation, with a sudden suppression of the coherent oscillations between atoms and molecules. We also show that the full quantum dynamics of the system is dominated by quantum fluctuations in the vicinity of the self-trapping solution.

We studied the dynamics of Bose-Einstein condensates in symmetric double-well potentials following a sudden change of the potential from the Mott-insulator to the superfluid regime. We introduce a continuum approximation that maps that problem onto the wave-packet dynamics of a particle in an anharmonic effective potential. For repulsive two-body interactions the visibility of interference fringes that result from the superposition of the two condensates following a stage of ballistic expansion exhibits a collapse of coherent oscillations onto a background value whose magnitude depends on the amount of squeezing of the initial state. Strong attractive interactions are found to stabilize the relative number dynamics. We visualize the dynamics of the system in phase space using a quasiprobability distribution that allows for an intuitive interpretation of the various types of dynamics.